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An Introduction to SnapTrack™ Server-Aided GPS Technology

BIOGRAPHY

Mark Moeglein received his B.S. in Engineering in 1987 from Harvey Mudd College. He has been developing GPS-related systems since 1989, and has been a primary developer of the SnapTrack™ LocationServer technology since joining the company in 1996.

Norman Krasner received his B.S. in Electrical Engineering from M.I.T. in 1968 and M.S. and PhD from Stanford University in 1970 and 1974. He has worked in the fields of signal processing and communication systems design for over 30 years, including design of many spread spectrum communication systems. He was a co-founder of SnapTrack™ in 1995 and is currently V.P. of Technology.

ABSTRACT

The distributed SnapTrack™ server-aided GPS system architecture and DSP software-based receiver solution draw from the best of GPS and wireless communications technology. The DSP-based receiver is superior to conventional correlator-based approaches in terms of cost, sensitivity, time-to-first-fix and power consumption. A smart server provides key aiding information and performs navigation solutions, minimizing incremental handset costs and providing for improved acquisition times, sensitivity, and accuracy. This paper will describe the advantages of these innovations and demonstrate the technology with a presentation of field test results.

INTRODUCTION

SnapTrack™ has developed a distributed server-aided DSP-based processing approach to the problem of locating wireless communication devices. The key advantages to this approach, when compared to conventional GPS, are:

1. *High sensitivity.* The SnapTrack™ system can acquire and provide fixes in conditions with as much as 25dB (a factor of 300) signal attenuation or blockage. Traditional GPS technology can have difficulty acquiring signals when the attenuation exceeds 5-10 dB. This signal sensitivity improvement allows SnapTrack™-enhanced GPS to operate in difficult environments, such as most buildings, inside automobiles, under dense foliage, and in urban canyons, where traditional GPS is unreliable or unusable.

2. *Low Time-To-First-Fix.* Traditional GPS receivers require from 30 seconds to several minutes to acquire and track satellites, depending upon how much information they have previously gathered. In worst case environments, the SnapTrack™ system provides a first fix in just a few seconds. In open-sky situations, the first fix can be performed in less than a second.

3. *Low power dissipation.* SnapTrack™ technology performs *Location On Demand,* using a snapshot of data (typically 0.1 to 1 second, depending on sensitivity required), and then turns off. The entire location operation

takes only a few seconds for a "cold start" in a heavily blocked signal environment, and is significantly faster if prior information (such as local oscillator offset) is known or signal strength is high (> 135dBm). Thus, in those applications which do not require continuous high-rate positioning, the low duty cycle SnapTrack™-enhanced GPS receiver dissipates a small fraction of the power of the communication device (e.g., a portable handset) with which it is mated.

CONVENTIONAL GPS

A GPS user positioning system can be broken into four primary functions:

(1) determining the code phases (pseudoranges) to the various GPS satellites,
(2) determining the time-of-applicability for the pseudoranges,
(3) demodulating the satellite navigation message, and
(4) computing the position of the receiving antenna using these pseudoranges, timing, and navigation message data.

Most commercial GPS receivers perform all of these operations without any external assistance. In these conventional receivers, the satellite navigation message, and its inherent synchronization bits, are extracted from the GPS signal after it has been acquired and tracked. But collecting this information normally takes thirty seconds to several minutes. Also, a high received signal level (approximately -135dBm or greater) is required from all satellites to be used in the navigation solution for the 18 second duration of subframes 1-3.

DISTRIBUTED SYSTEM CONCEPT

The SnapTrack™ server-aided system architecture distributes the four primary functions described above between a GPS reference receiver, a location server, and a wireless GPS-enabled device (later referred to as a handset.) The basic system model is described in Figure 1.

A GPS reference receiver gathers navigation message and differential correction data for all satellites in view. In another system configuration, the GPS reference receiver may be replaced by a network of reference receivers to provide coverage for a wide area, such as the continental U.S.

The location server receives and stores data from the GPS reference receiver (or network), provides aiding data to mobile units, and performs navigation solutions upon receipt of pseudorange measurements from the handset.

The aiding data, sent to each handset on-demand, is generally a list of satellites in view from the handset and their relative Doppler offsets. (Estimated Doppler can be improved by using the location of the base station communicating with the hand-held device as an approximate handset location.) This small message (approximately 50 bytes) is all the handset needs to know from the location server to extract pseudorange information from its short snapshot of GPS data.

The server also has access to a terrain elevation database. This allows it to perform accurate altitude aiding for ground-based applications, a capability that is impractical if the navigation solution is performed at the mobile. The terrain elevation provides essentially an extra range measurement, improving reliability and accuracy.

The server is able to mitigate multipath and reflected signal effects using a sequential measurement optimization (SMO) technique. The server also handles cross-correlations from strong signals onto the PRN codes of weaker satellites, as well as correcting for atmospheric delays.

In general, the location server is remote from the final application, such as service centers providing display and operator services.

The wireless GPS-enabled device can track far weaker GPS signals than a conventional GPS receiver, because it does not need to decode the navigation message. But

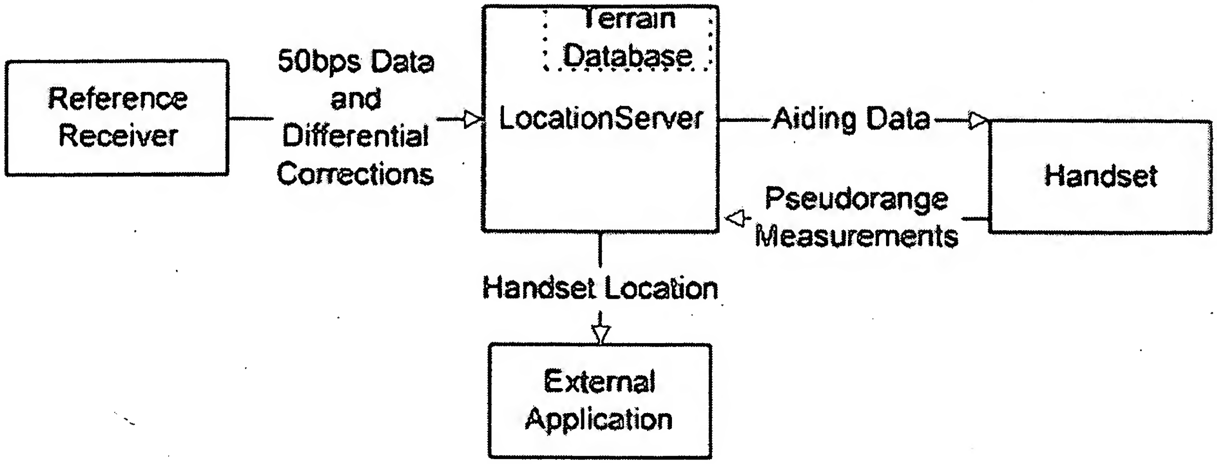

Figure 1 Basic system model

rapidly and accurately finding these weaker signals requires a powerful signal processing element to search over the large number of PRN codes, times-of-arrival, and offset frequencies (due to Doppler errors and local oscillator frequency errors). The DSP-based process for determining pseudoranges is described later in this paper.

CONVENTIONAL GPS CORRELATION TECHNIQUES

Conventional GPS receivers use correlation methods to compute pseudorange. A classic hardware correlator-based receiver multiplies the received signal by a stored (or generated) replica of the appropriate PRN code and then integrates, or lowpass filters, the product to obtain a peak correlation signal. The initial determination of the presence of a correlation peak is termed "acquisition."

Once a signal is acquired, the process enters the tracking mode in which the PRN code is removed, or "despread." This signal has a narrow bandwidth, commensurate with the 50 bit per second navigation message modulated onto the GPS waveform. At this point, the navigation message may be reliably demodulated if received signal strength is above approximately -135dBm for the duration of the message being received.

The conventional acquisition process is very time consuming, especially if received signals are weak. To improve acquisition time, most GPS receivers utilize a multiplicity of correlators (nominally ~36 for a 12-channel receiver), which allows a parallel search for correlation peaks as a function of time-of-arrival, PN code, and frequency offset. Recently, massively parallel correlators (on the order of 240) have been used to improve acquisition speed and sensitivity. In excess of 8000 correlators would be required to match the speed and sensitivity of the SnapTrack™ server-aided GPS fast convolution processing technique. And the processing speed or this technique will improve as DSP technology advances.

HANDSET ARCHITECTURE

Figure 2 is a "handset view" of the SnapTrack™ server-aided GPS system. Note that the conventional tracking loops are replaced by snapshot memory and fast convolution processing.

At the request of either an external application, or the handset user, the server sends information on satellites in view at the handset's approximate location, including Doppler predictions. After a snapshot of GPS satellite RF data has been stored in the handset memory, the DSP processes the data and returns pseudorange measurements to the server, along with other statistical information. This snapshot approach allows the handset to gather GPS data when it is not transmitting, thus eliminating potential self-interference.

Each of the messages between the handset and the location server is small (50-100 bytes). This represents a significant reduction in required communications bandwidth when compared to delivering differential corrections, almanac, ephemeris and/or satellite trajectory data to the handset.

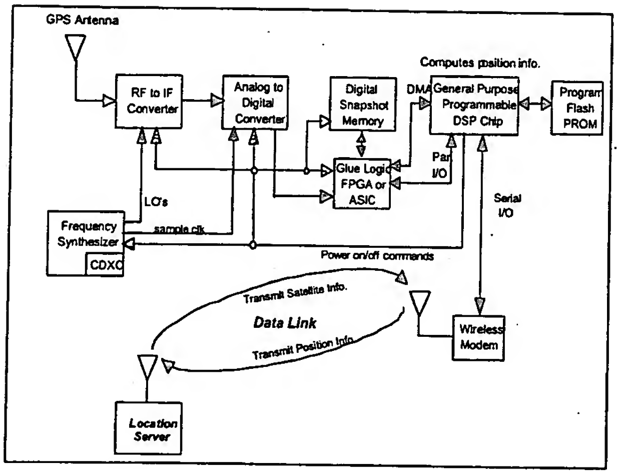

Figure 2 Block diagram of DSP-based GPS processing system

FFT-based fast convolution techniques provide higher sensitivity and faster acquisition speed by performing a large number of FFT operations together with special pre- and post-processing operations [1]. It is expected, in a worst-case example, that pseudorange in the DSP will require approximately 5 seconds, with much faster performance in situations with higher (> -135dBm) signal strength or DSP speed.

In the system described in Figure 2, received data is down-converted to a suitably low (~2MHz) intermediate frequency, digitized and stored in a buffer memory. This data is then operated upon using a programmable DSP IC. Unlike continuously tracking hardware correlator-based receivers, this "snapshot" processing technique is not subject to the fluctuating signal levels and changing nature of the signal environment.

Each received GPS signal (C/A code) is constructed from a high rate (1 MHz) repetitive pseudorandom noise (PRN) pattern of 1023 symbols, commonly called "chips." These "chips" resemble the waveform shown in Figure 3A. Further imposed on this pattern is low rate data, transmitted from the satellite at 50 baud. All of this data is received at a very low signal-to-noise ratio as measured in a 2 MHz bandwidth. If the carrier frequency and all data rates were known to great precision, and no data were present, then the signal-to-noise ratio could be greatly improved by summing successive frames. For example, there are 1000 C/A code epochs over a period of 1 second. The first such epoch could be coherently added to the next, the result added to the third, etc. The result would be a signal having duration of 1023 chips. The phasing of this sequence could then be compared to a local reference sequence to determine the relative timing between the two, thus establishing the pseudorange. Doppler and local oscillator uncertainty complicate this process. The server reduces these uncertainties by providing Doppler estimates.

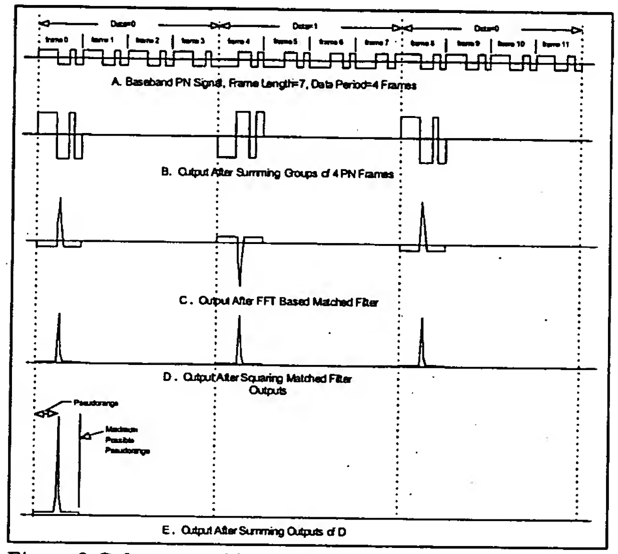

Figure 3 Coherent and incoherent summation with matched filtering.

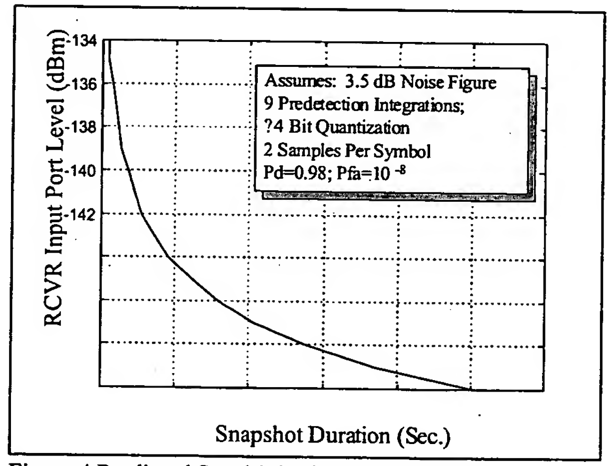

Figure 4 Predicted Sensitivity in Thermal Noise

The above process is carried out separately for each satellite in view from the same set of data in the snapshot memory, since, in general, the GPS signals from different satellites have different Doppler frequencies and the PRN patterns differ from one another.

The presence of 50-baud data superimposed on the GPS signal limits the coherent summation of C/A code epochs

to a period of 20 msec. That is, at most 20 one-millisecond-long epochs may be coherently added before data sign inversions prevent further coherent summation (unless this data is provided by the server). Additional processing gain may be achieved through summation of the magnitudes (or squares of magnitudes) of the coherently summed intervals, providing the sensitivity and accuracy shown in the curves of Figures 4 and 5.

A calibrated single-satellite GPS simulator and a demonstration system designed by SnapTrack™ were used to experimentally verify the performance predicted in Figure 4. The 20-meter accuracy predicted by Figure 5 with a 1-second snapshot and –150dBm signal strength was also demonstrated in later field testing.

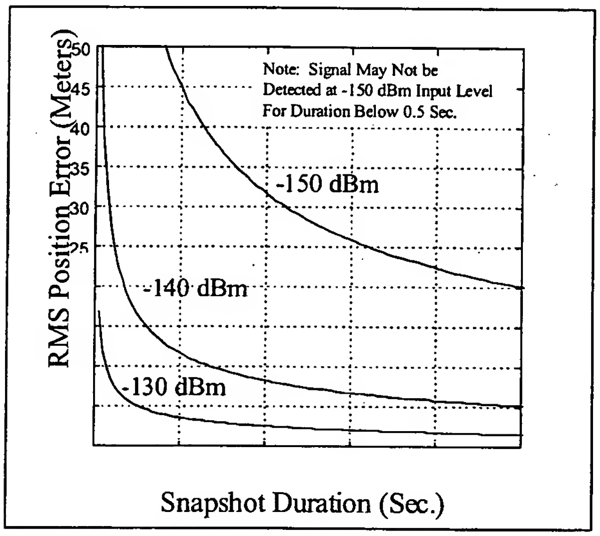

Figure 5 Predicted accuracy in thermal noise, HDOP=1.5

FIELD TEST RESULTS

The SnapTrack™ demonstration system was used extensively for field tests designed and audited by independent wireless carriers. Environments ranging from open sky to in-vehicle, indoor and urban canyon were investigated.

Table 1 summarizes test results from seven test locations visited over the past year. These selected results are representative of a much broader range of tests.

The test setup consisted of a 12-channel reference receiver transmitting reference data to a PC-based location server, which communicated with a SnapTrack™ sensor via modem over an analog cellular phone connection. The SnapTrack™ sensor used an off-the-shelf active patch antenna, and a long cable, which allowed testers to place the antenna in hard-to-reach places. Preliminary results indicate similar performance with a "micro-helix" passive antenna, which is more suitable for handset integration[2].

Environment	Conditions	Yield	68.3% Horizontal Error
Outdoors	Open site	100%	4 meters
Urban Street, Shinbashi, Tokyo	2-10 story buildings, narrow streets and alleys	100%	15 meters
Inside Sport Utility Vehicle	Parking lot surrounded by red wood trees and two-story buildings. Antenna placed on inside shoulder	100%	17 meters
Two Story House	Center of basement	100%	20 meters
Two-Story Office Building	1st floor, interior room	94%	22 meters
Urban Canyon, Denver, CO	20-30 story buildings, wide streets, altitude aided	98%	29 meters
50-Story Building	Glass/Steel building, 21st floor, 14 ft from outside wall	89%	84 meters

Table 1 Field test results summary

The system was operated such that no information was carried over for each successive sample. Thus, each successive snapshot can be considered an independent "first fix." A more detailed description of each location

(with the exception of the outdoor, open sky environment) follows, with plots of the horizontal "shot pattern" from each location.

Figure 6a One-lane urban road

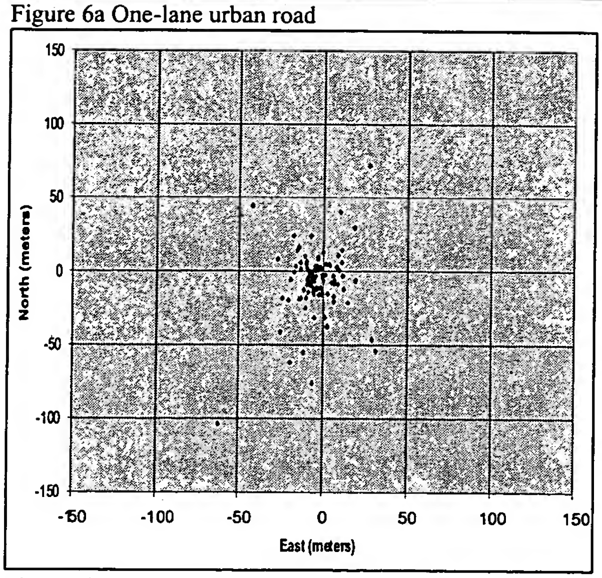

Figure 6b Shot pattern, one-lane urban road

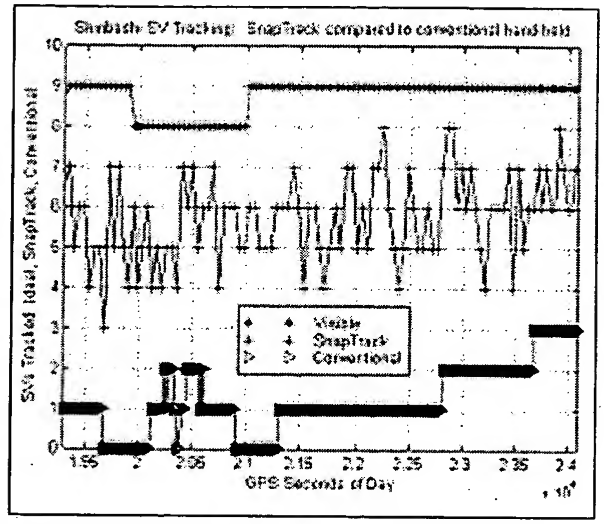

Figure 6c Satellites tracked by SnapTrack sensor and conventional hand-held

Test location: one-lane urban road

A Japanese wireless carrier selected the site depicted in Figure 6a to represent a fairly typical Tokyo environment. The antenna was placed approximately 3 feet above the ground on the side of a one-lane road, surrounded by 2-10 story buildings.

A conventional handheld GPS receiver was used for comparison purposes. This receiver was allowed to operate continuously throughout the data collection, resting horizontally (antenna facing the sky) near the antenna used for the SnapTrack handset.

Results in Figure 6c show the conventional receiver tracking 14.3% of the satellites in view over the data collection period, while the SnapTrack handset was able to acquire 65.3% of satellites on "cold starts" throughout the data collection interval.

Test location: sport utility vehicle

Figure 7a shows one of several test vehicles used in SnapTrack™ parking lot in-vehicle testing. This lot has moderate blockage from a two-story building, as well as several redwood trees overhead. Resultant accuracy is similar to that observed in most indoor tests.

Figure 7a Sport utility vehicle

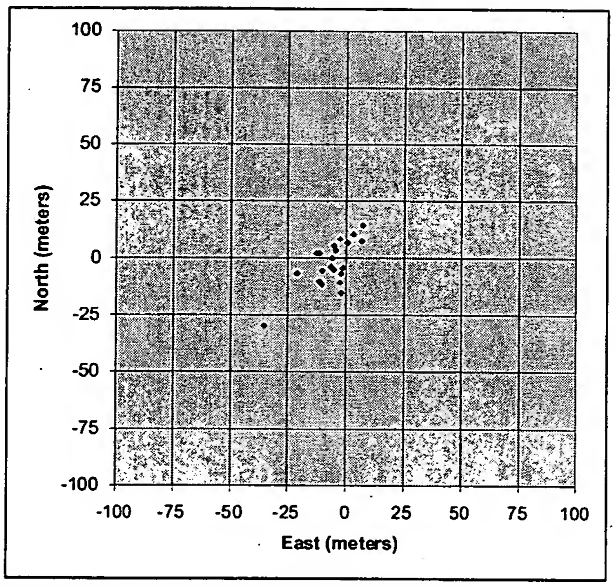

Figure 7b Shot pattern, sport utility vehicle

Figure 8a Westminster (Denver), Colorado house

Figure 8b GPS Antenna at center of basement

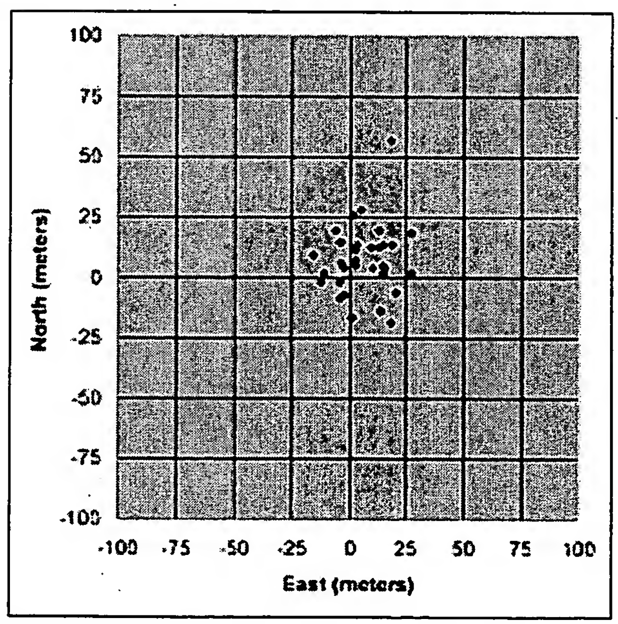

Figure 8c Shot pattern, basement of two-story house

Test location: basement of two-story residence
U.S. West selected the house in Figure 8a as a sample residence in the Denver area. As shown in Figure 8b, the antenna was placed in the center of the basement. (The 5-watt analog phone had to be placed outside to maintain enough signal strength for data connectivity.) Figure 8c shows system performance in this location.

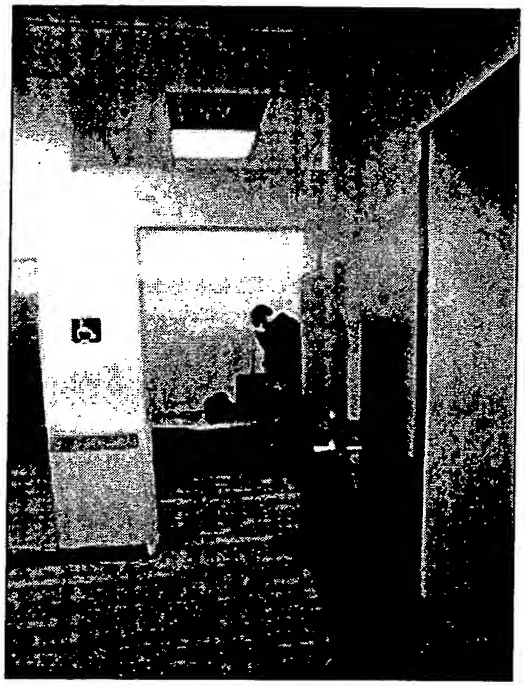

Figure 9a Two-story brick building, interior first floor

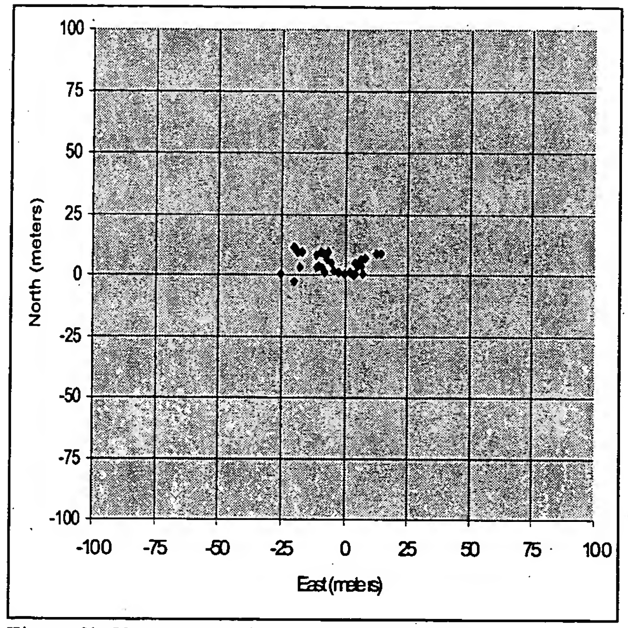

Figure 9b Shot pattern, first floor interior room

Test Location: Two-story office building, interior
Figure 9 shows the location and results of this test in a two-story commercial brick building. As expected, the accuracy is comparable to most residential locations. The test equipment was placed in an interior first-floor room.

Test location: urban canyon
Figure 10a illustrates a somewhat typical downtown environment. Figure 10b and Figure 10c demonstrate server-aided system performance in this environment with and without altitude aiding. In this test case, altitude aiding resulted in a 30% accuracy improvement. In weaker signal environments, altitude aiding is very important, improving satellite geometry, as well as providing a reliable extra measurement in the navigation solution.

Figure 10a Urban canyon, downtown Denver

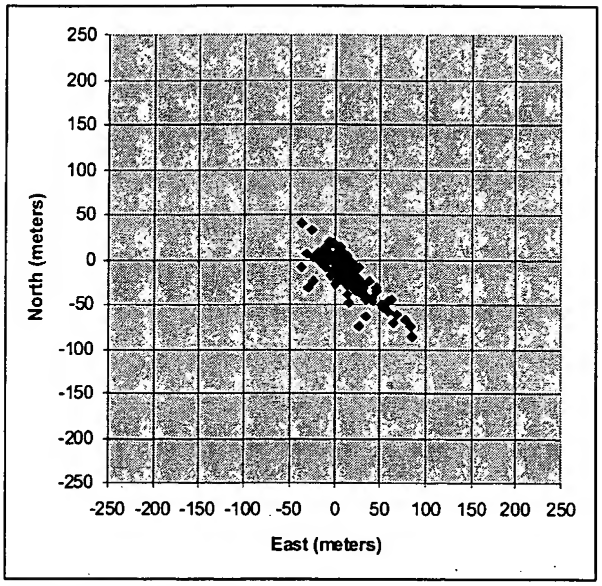

Figure 10b Shot pattern, urban canyon, altitude aided

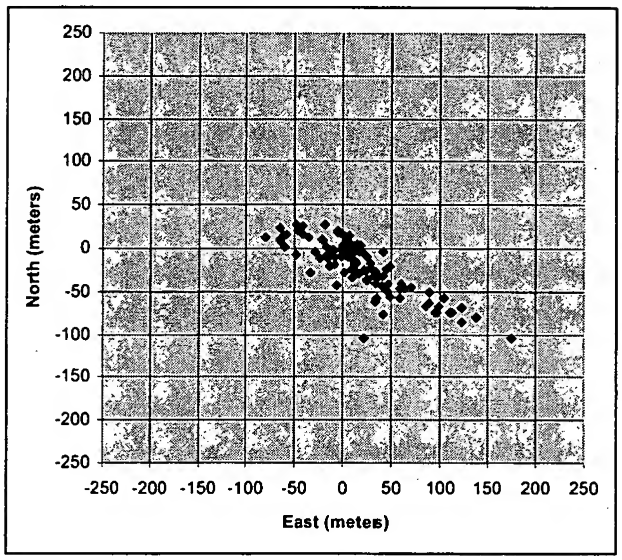

Figure 10c Shot pattern, urban canyon, unaided

Test Location: 50-Story Glass/Steel Building, 21st floor, 14 feet from outside wall

Figure 11a illustrates a signal environment with poor signal strength and long multipath. In previous tests, either the signal strength (and therefore often the geometry) or path length differences were poor. In this case, 14 feet from the outside wall on the 21st floor of this building, both problems were evident, creating greater position biases due to reflections from a south-facing building, as shown in Figure 11b.

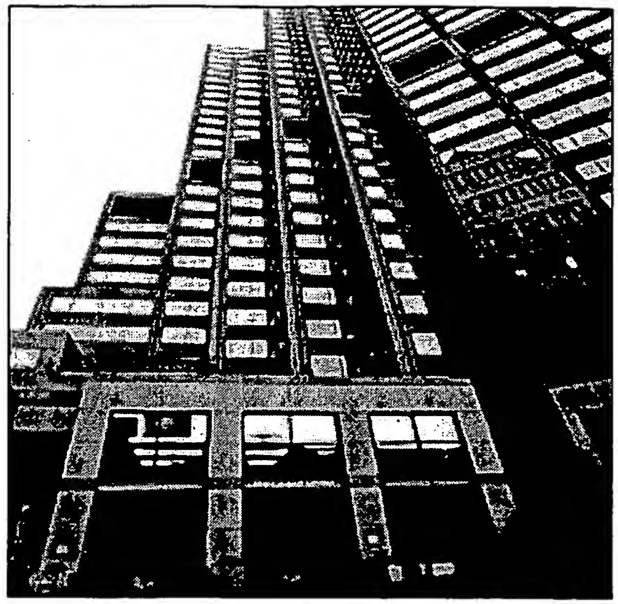

Figure 11a Fifty story glass/steel building

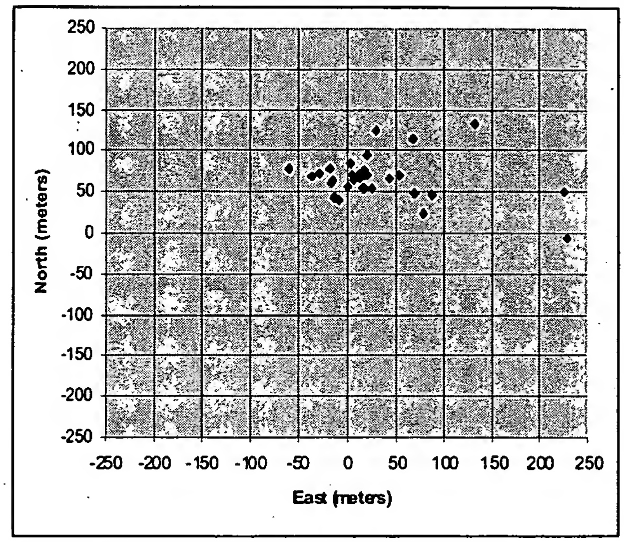

Figure 11b Shot pattern, inside 50-story building

Denver E-911 Trial

SnapTrack™ provided the enabling GPS technology for a recent end-to-end wireless E-911 trial conducted in the Denver area. Figure 12 is a good illustration of how the SnapTrack™ distributed system architecture can be used.

For this demonstration, a single reference receiver provided reference information to a location server. The SnapTrack™ sensor was programmed with the Mobile Identification Number (MIN) of an accompanying digital phone, so that their separate calls could later be matched by the SignalSoft Service Control Point (SCP). (In this

case, the analog phone provided communication services to the SnapTrack sub-handset and the digital phone

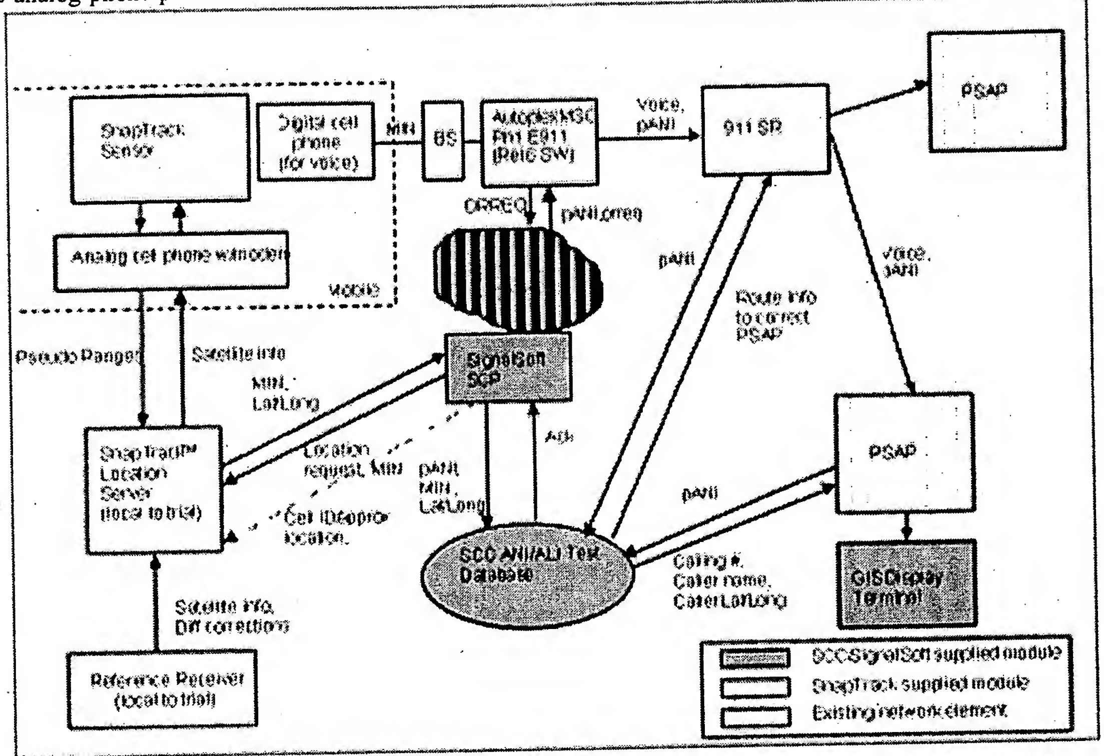

Figure 12 Denver E-911 trial system

provided E911 functionality.) When the mobile user placed a call to the Public Safety Access Point (PSAP), the two pieces of information were combined into a single call by the SCP when presenting the information to the SCC database. This database provided call routing instructions for the digital cell phone's 911 voice call. The SCP was able to determine which PSAP should receive each call using the location information from the LocationServer and a digital map of PSAP coverage boundaries. The SCC ANI/ALI database also provided the handset location to the selected PSAP, pin-pointing the caller location on a GIS map display.

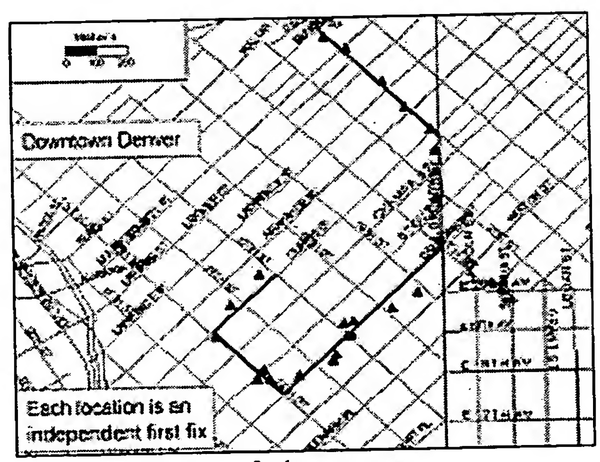

Figure 13 Driving out of urban canyon

Figure 13 shows results from driving through an urban canyon in downtown Denver. The small clusters of points in Figure 13 are located near stop lights on the route out of downtown. Figure 14 illustrates the results of dynamic vehicle testing on an urban highway.

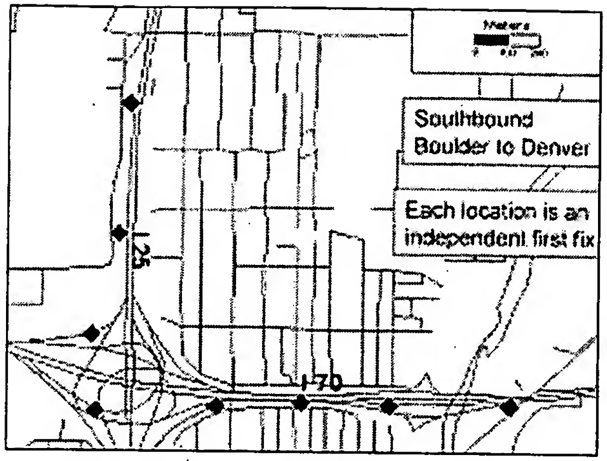

Figure 14 Urban highway

SUMMARY

SnapTrack™ server-aided GPS improves upon conventional GPS performance by sharing processing and database functions between the mobile GPS receiver/processor (the client) and a remote infrastructure (the server and reference network). The result is a highly sensitive, cost-effective, low-power, GPS receiving system that provides first fixes in a few seconds from a cold start, even where conventional GPS is unworkable or unreliable.

Audited field test results demonstrate accuracy of 3-100 meters (depending on degree of blockage), which is substantially better than the 125 meters required by the recent FCC E911 mandate, even in severe blockage and multipath environments.

REFERENCES

[1] Krasner, Patent 5,663,734

[2] Krasner, Wolf, Bell, and Wilson, "SnapTrack Enhanced GPS Technology: Field Test Results Using Prototype GPS Handset Antenna, Including the Impact of User Head Blockage.", submitted to the T1P1.5 GSM Working Group, August 17, 1998